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RESEARCH MEMORANDUM

THEORETICAL ROCKET PERFORMANCE OF JP-4 FUEL WITH MIXTURES OF LIQUID OZONE AND FLUORINE

By Vearl N. Huff and Sanford Gordon

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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THEORETICAL ROCKET PERFORMANCE OF JP-4 FUEL WITH MIXTURES OF LIQUID OZONE AND FLUORINE

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SUMMARY

Theoretical rocket performance was calculated for JP-4 fuel with mixtures of ozone and fluorine. The data were estimated by means of a heat-correction equation using data for JP-4 fuel with mixtures of oxygen and fluorine. The estimated values were checked with several direct calculations. The estimated data were based upon equilibrium composition during expansion, while the directly computed data were obtained for both equilibrium and frozen composition during expansion.

The maximum value of specific impulse was 334.9 pound-seconds per pound for a combustion-chamber pressure of 600 pounds per square inch absolute and an exit pressure of 1 atmosphere.

INTRODUCTION

Liquid-fluorine - liquid-ozone mixtures might serve as high-energy oxidants for rocket propellants. A mixture of liquid fluorine and liquid oxygen has been shown to give better performance with hydrocarbons than either 100 percent fluorine or oxygen (ref. 1). This is due to the preferential burning of fluorine with hydrogen and oxygen with carbon.

The substitution of liquid ozone for liquid oxygen provides the advantages of greater energy and density. Available information indicates that liquid-fluorine - liquid-ozone mixtures may be stable. If stable mixtures can be produced, this oxidant might have practical application. The performance of fluorine-ozone mixtures on the assumption of chemical equilibrium during expansion may be obtained from the performance of fluorine-oxygen mixtures for chemical equilibrium by applying a simple correction for the increased heat of reaction. A formula for such a correction is given in reference 2. The present report gives the specific impulse of fluorine-ozone mixtures with JP-4 fuel obtained with this correction equation and compares it with several direct computations.

CALCULATION OF PERFORMANCE DATA

The performance data presented in this report were calculated by two methods. The first method estimates performance by means of a heat-correction equation. The second method obtains performance by direct calculation.

Estimated Performance

Specific-impulse data for fluorine-oxygen mixtures with JP-4 fuel 4192
were corrected for the difference in heat of reaction between oxygen and ozone to obtain estimated data for fluorine-ozone mixtures with JP-4 fuel. The heat required to convert 1 gram of liquid oxygen at its boiling point to liquid ozone at its boiling point is about 726 calories per gram (ref. 3). The difference in heat per gram of propellant due to the use of ozone instead of oxygen is given by

$$\Delta h = 726\ (1 - x)\ y \tag{1}$$

where x is the weight fraction of fuel in the propellant and y is the weight fraction of ozone in the oxidant. (Symbols are defined in the appendix.) The specific impulse corrected for this energy difference is given by

$$I^2 = I_1^2 + a\ \Delta h + b\ \Delta h^2 \tag{2}$$

where

$$a = 87.0132 \left(1 - \frac{T_e}{T_c}\right)_1$$

$$b = \frac{87.0132}{2} \left(\frac{T_e}{T_c^2}\right)_1 \left[\frac{1}{(c_p)_c} - \frac{1}{(c_p)_e}\right]_1$$

and the subscript 1 indicates the value of the parameters before the change is made. Equation (2) is derived in reference 2 and is restricted to the assumption of chemical equilibrium during expansion. A numerical example of the use of equation (2) is given in reference 4.

The value of 726 calories per gram used in equation (1) was obtained from heat of formation and heat of vaporization data in reference 5 and specific heat data for ozone calculated from spectroscopic data of reference 6. More recent data quoted in reference 7 give a value of 711

calories per gram. This difference affects specific impulse in this report by less than 0.25 pound-second per pound.

Direct Computation of Performance

The estimated performance data obtained by means of equation (2) were checked by several direct calculations. The general method used to obtain directly computed data is described in reference 3.

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Assumptions. - The calculations were based on the following usual assumptions: perfect gas law, adiabatic combustion at constant pressure, isentropic expansion, no friction, homogeneous mixing, and one-dimensional flow. The products of combustion were assumed to be graphite and the following ideal gases: atomic carbon C, carbon monofluoride CF, carbon difluoride CF_2, carbon trifluoride CF_3, carbon tetrafluoride CF_4, difluoroacetylene C_2F_2, methane CH_4, carbon monoxide CO, carbon dioxide CO_2, atomic fluorine F, fluorine F_2, atomic hydrogen H, hydrogen H_2, hydrogen fluoride HF, water H_2O, atomic oxygen O, oxygen O_2, and the hydroxyl radical OH. The combustion products were assumed to be expanded completely within the exit nozzle, that is, exit pressure equals ambient pressure. The graphite was assumed to be finely divided and in temperature and velocity equilibrium with the gases during the flow process.

Thermodynamic data. - The thermodynamic data for all combustion products except graphite, methane, the fluorocarbons, and water were taken from reference 3. Data for graphite were taken from reference 8, carbon monofluoride from reference 9, the remainder of the fluorocarbons from reference 10, and water from reference 11. Data for methane were determined by the rigid-rotator - harmonic-oscillator approximation using spectroscopic data from reference 6. The base used in this report for assigning absolute values to enthalpy is the same as in reference 3.

The dissociation energy of fluorine was taken to be 35.6 kilocalories per mole, and the heat of sublimation of graphite at 298.16° K was taken to be 171.698 kilocalories per mole (ref. 5). The heat of solution of oxygen and fluorine was taken to be zero.

Viscosity data. - The theoretical viscosities for the gases in this report were calculated by means of three types of equations or estimated. The viscosity data for CH_4, CO, CO_2, F_2, H_2, and O_2 were calculated by the method of reference 12. The viscosities of C, F, H, HF, O, and OH were calculated by the method of reference 13, which assumes that the logarithm of viscosity is a linear function of the logarithm of temperature. The viscosity of H_2O was obtained by means of a Sutherland equation (ref. 14). The viscosities of CF, CF_2, CF_3, CF_4, and C_2F_2 were

taken to be equal to those of CO, CO_2, CH_3, CH_4, and C_2H_2, respectively. The method used to obtain the viscosities and conductivities of mixtures of combustion products is given in reference 4.

Physical and thermochemical data. - The properties of the fuel used in these calculations are typical of the JP-4 fuel delivered to this laboratory over a period of 2 years. The JP-4 fuel was assumed to have a hydrogen-to-carbon weight ratio of 0.163 (atom ratio of 1.942), a lower heat of combustion value of 18,640 Btu per pound, and a specific gravity of 0.769. Additional properties of jet fuels may be found in reference 15.

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Several properties of fluorine and ozone taken from references 3, 5, 7, and 16 are listed in table I. Additional data on ozone may be found in reference 7.

Method of calculation. - The calculation procedures and the formulas used are the same as described in reference 4.

Accuracy of results. - The values presented for enthalpy, entropy, and specific impulse appear to be computed correctly to all figures tabulated. The temperature and molecular weight may in some cases be in error by a few figures in the last place tabulated. The derivatives may, in regions where they are changing rapidly, be in error by a few percent. However, because of uncertainties in thermodynamic data used, all values are probably tabulated to more places than are entirely significant.

THEORETICAL PERFORMANCE DATA

Tables

The theoretical specific impulse obtained by direct calculation and estimated by means of equation (2) is given in table II. The data used in equation (2) were obtained from results previously computed at this laboratory both published (refs. 1 and 4) and unpublished (including specific heat data for ref. 1). The estimated values of specific impulse are from 0.2 to 0.8 pound-second per pound lower than the directly calculated values for the five points for which both values were calculated. It is expected that the other estimated values given in table II are in error by about the same amount.

The maximum value of specific impulse is 334.9 pound-seconds per pound for a combustion-chamber pressure of 600 pounds per square inch absolute and an exit pressure of 1 atmosphere.

The calculated values of performance parameters and combustion products obtained by direct calculations are given in tables III to VI.

The properties of gases in the combustion chamber and the characteristic velocity are given in table III. The equilibrium values of specific heat, isentropic exponent, and characteristic velocity include the energy of dissociation. The equilibrium specific heat was calculated by means of equation (37) in reference 3. The equilibrium isentropic exponent $\gamma = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$ was computed by means of equation (32) in reference 3. The frozen values of specific heat, isentropic exponent, and characteristic velocity do not include the energy of dissociation and are computed by the conventional formulas (see ref. 17).

Tables IV and V present the values of performance parameters and combustion products at assigned temperatures and constant entropy. The values were computed directly and used to interpolate properties at the assigned pressure ratios given in table VI. A discussion of the use of derivatives such as n_I, n_T, and $(\partial M/\partial T)_s$ is given in reference 4. Mole fractions were computed for all 19 substances considered in this report, but those substances are omitted from table V whose mole fractions are less than 5×10^{-6} for all temperatures shown for a given equivalence ratio r and fluorine-to-oxygen atom ratio β.

Table VI presents performance data at various assigned pressure ratios from 1 to 300. Reference 4 gives an example of the use of data at the low pressure ratios to obtain pressures at the injector face.

Figures

The specific-impulse data of table II for a pressure ratio of 20.41 are plotted in figure 1. The maximum value of specific impulse is 309.0 at an equivalence ratio of 1.508 for a fluorine-to-oxygen atom ratio of 1.942.

Figure 2 presents the maximum value of specific impulse for any percent fluorine in the oxidant. A curve of maximum specific impulse for oxygen instead of ozone is given for comparison.

The increase in maximum specific impulse due to the substitution of ozone for oxygen is summarized in the following table (combustion-chamber pressure, 600 lb/sq in. abs; exit pressure, 2 atm; pressure ratio, 20.41):

Fluorine in oxidant, percent by weight	Specific impulse, I, lb-sec/lb		Increase in specific impulse, lb-sec/lb
	JP-4 fuel plus fluorine-oxygen mixture	JP-4 fuel plus fluorine-ozone mixture	
0	262.3	284.3	22.0
40	281.7	295.4	13.7
70	301.0	309.0	8.0

Figures 3 and 4 present data computed by direct methods. Figure 3 shows specific impulse as a function of the logarithm of pressure ratio for frozen and equilibrium composition during expansion. The equilibrium values are from about 7 to 12 percent higher than the frozen values. The specific-impulse exponent n_I is also given.

Figure 4 presents temperature plotted against the logarithm of pressure ratio for frozen and equilibrium composition during expansion. Also shown is the temperature exponent n_T.

SUMMARY OF RESULTS

Rocket performance data are presented for JP-4 fuel with mixtures of ozone and fluorine. Specific-impulse data were estimated by means of a heat-correction equation from data for JP-4 fuel with mixtures of oxygen and fluorine. The estimated data were checked for several cases by direct calculations. The difference in specific impulse between the estimated and directly calculated values was from 0.2 to 0.8 pound-second per pound. This difference is negligible for many applications.

The maximum specific impulse for a combustion-chamber pressure of 600 pounds per square inch absolute is 309.0 and 334.9 pound-seconds per pound for pressure ratios of 20.41 and 40.83, respectively.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 26, 1956

APPENDIX - SYMBOLS

A	nozzle area, sq in.
C_F	coefficient of thrust; $C_F = g_c I/c^* = F/P_c A_t$
c_p	specific heat at constant pressure, $(\partial h/\partial T)_P$, cal/(g)(°K)
c^*	characteristic velocity, $g_c P_c A_t/w$, ft/sec
F	thrust, lb
g_c	gravitational conversion factor, 32.174 (lb mass/lb force)(ft/sec^2)
H_T^o	sum of sensible enthalpy and chemical energy, cal/mole
h	sum of sensible enthalpy and chemical energy per unit mass, $\dfrac{\sum_i n_i (H_T^o)_i}{M(1 - n_k)}$, cal/g
I	specific impulse, lb force-sec/lb mass
M	molecular weight, $\dfrac{\sum_i n_i M_i}{1 - n_k}$, g/g-mole or lb/lb-mole
$\left(\dfrac{\partial M}{\partial T}\right)_s$	derivative of molecular weight with respect to temperature at constant entropy, $(°K)^{-1}$
n	mole fraction
n_I	specific-impulse exponent for fixed pressure ratio, $\left(\dfrac{\partial \ln I}{\partial \ln P_c}\right)_{P_c/P}$
n_T	temperature exponent for fixed pressure ratio, $\left(\dfrac{\partial \ln T}{\partial \ln P_c}\right)_{P_c/P}$
P	static pressure (sum of partial pressures), lb/sq in.
p	partial pressure, lb/sq in.

R	universal gas constant (consistent units)
r	equivalence ratio, ratio of four times the number of carbon atoms plus the number of hydrogen atoms to two times the number of oxygen atoms plus the number of fluorine atoms in propellant, $\frac{4(C) + (H)}{2(O) + (F)}$
S_T^o	entropy at pressure of 1 atmosphere, cal/(mole)(^oK)
s	entropy per unit mass, $\frac{\sum_i n_i(S_T^o)_i}{M(1 - n_k)} - \frac{R\sum_j p_j \ln(p_j/14.696)}{PM}$
T	temperature, ^oK
w	mass-flow rate, lb/sec
x	weight fraction of fuel in propellant
y	weight fraction of ozone in oxidant
α	oxidant-to-fuel mole ratio
β	fluorine-to-oxygen atom ratio
γ	isentropic exponent, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$
ρ	density, lb/cu in.

Subscripts:

c	combustion chamber
e	nozzle exit
i	product of combustion including both gaseous and solid phases
j	gaseous product of combustion
k	solid product of combustion (graphite)
P	constant pressure
P_c/P	constant pressure ratio

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s constant entropy

t nozzle throat

1 reference point

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TABLE I. - PROPERTIES OF OXIDANTS

Properties	Fluorine	Ozone
Molecular weight, M	38.00	48.00
Density, g/cc	[a]1.54	[b]1.46 [c]1.571
Freezing point, °C	[d]-217.96	[e]-192.7
Boiling point, °C	[d]-187.92	[d]-110.51
Enthalpy required to convert liquid at boiling point to gas at 25° C, kcal/mole	[f]3.030	[f]3.8
Enthalpy of vaporization, kcal/mole	[g]1.51	[h]2.59
Enthalpy of fusion, kcal/mole	[i]0.372	

[a]At -196° C (ref. 16).
[b]At -112° C (ref. 7).
[c]At -183° C (ref. 7).
[d]Ref. 5.
[e]Ref. 7.
[f]Ref. 3.
[g]At -187.92° C (ref. 5).
[h]At -110.51° C (ref. 5).
[i]At -217.96° C (ref. 5).

TABLE II. - THEORETICAL SPECIFIC IMPULSE OF JP-4 FUEL WITH MIXTURES OF LIQUID FLUORINE AND OZONE

[Combustion-chamber pressure, 600 lb/sq in. abs.]

Fluorine-to-oxygen atom ratio, β	Fluorine in oxidant, percent by weight	Equivalence ratio, r, $\frac{4(C)+(H)}{2(O)+(F)}$	Fuel in propellant, percent by weight	Specific impulse estimated by equation (2) for equilibrium composition		Specific impulse by direct computation			
						Equilibrium composition		Frozen composition	
				Pressure ratio					
				20.41	40.83	20.41	40.83	20.41	40.83
0	0	1.000	22.71	270.9	295.4				
		1.200	26.07	277.4	302.2				
		1.300	27.64	279.7	305.8				
		1.400	29.15	281.1	306.5				
		1.508	30.70	283.2		284.0	308.9	269.8	290.0
		1.600	31.98	284.3	309.0				
		1.800	34.59	283.3	306.5				
0.200	19.19	1.500	28.15	287.8	312.7				
		1.508	28.26	287.8					
		1.540	28.68	288.0					
0.500	37.25	1.500	25.69	293.8	319.0				
		1.508	25.78	293.8		294.5	319.8	277.2	297.0
		1.600	26.94	294.2					
1.000	54.29	1.500	23.21	301.0	325.7				
		1.508	23.30	301.1		301.4	327.0	282.2	302.5
		1.550	23.80	301.3					
		1.600	24.38	301.4					
1.600	65.52	1.500	21.48	306.9	332.6				
		1.508	21.57	307.0					
		1.530	21.82	307.0					
		1.600	22.59	307.7					
		1.700	23.67	304.9					
1.942	69.75	1.470	20.48			308.0	333.9	287.2	306.8
		1.500	20.81	308.6		309.0	334.9	288.1	307.8
		1.508	20.89	308.7	334.5	308.9	334.8	288.1	307.8
		1.520	21.03	308.3					
2.000	70.37	1.000	14.83	282.8	305.8				
		1.400	19.60	305.7	331.0				
		1.500	20.71	308.2	334.0				
		1.600	21.79	305.9	331.9				
		2.500	30.33	289.7	313.0				
2.100	71.38	1.400	19.44	305.1					
		1.500	20.55	306.5					
		1.530	20.87	305.9					
		1.570	21.28	305.3					
2.200	72.32	1.450	19.85	305.5					
		1.500	20.40	305.1					
		1.540	20.82	304.6					
		1.600	21.46	304.0					
2.500	74.80	1.650	21.56	301.1					
		1.700	22.07	301.1					
		1.750	22.57	301.1					
4.000	82.61	2.000	23.47	294.3	320.1				
		2.040	23.82	294.4					
		2.200	25.22	294.1					

TABLE III. - THERMODYNAMIC PROPERTIES OF COMBUSTION GASES FOR JP-4 FUEL AND MIXTURES OF LIQUID FLUORINE AND OZONE

[Combustion-chamber pressure, 600 lb/sq in. abs.]

Fluorine-to-oxygen atom ratio, β	Fluorine in oxidant, percent by weight	Equivalence ratio, r, $\frac{4(C) + (H)}{2(O) + (F)}$	Fuel, percent by weight	Temperature T, $^{\circ}K$	Molecular weight, M	Enthalpy, h, cal/g	Entropy, s, $\frac{cal}{(g)(^{\circ}K)}$	Specific heat, c_p, $\frac{cal}{(g)(^{\circ}K)}$	Isentropic exponent, γ	Characteristic velocity c^*, ft/sec
Equilibrium composition										
								(a)	(a)	(a)
0	0	1.508	30.70	3831	20.74	3914	2.954	1.887	1.145	6383
.5	37.25	1.508	25.78	4100	20.31	3636	2.903	1.665	1.162	6637
1.0	54.29	1.508	23.30	4329	20.26	3495	2.845	1.485	1.171	6809
1.942	69.75	1.47	20.48	4602	20.62	3319	2.749	1.481	1.169	6964
1.942	69.75	1.50	20.81	4609	20.52	3355	2.758	1.490	1.168	6985
1.942	69.75	1.508	20.89	4606	20.51	3359	2.759	1.494	1.167	6986
Frozen composition										
								(b)	(b)	(b)
0	0	1.508	30.70	3831	20.74	3914	2.954	0.4992	1.238	6198
.5	37.25	1.508	25.78	4100	20.31	3636	2.903	.4522	1.276	6407
1.0	54.29	1.508	23.30	4329	20.26	3495	2.845	.4290	1.296	6555
1.942	69.75	1.47	20.48	4602	20.62	3319	2.749	.4046	1.313	6670
1.942	69.75	1.50	20.81	4609	20.52	3355	2.758	.4069	1.312	6691
1.942	69.75	1.508	20.89	4606	20.51	3359	2.759	.4074	1.312	6690

[a]Energy of dissociation included in computation of property value.

[b]Energy of dissociation excluded in computation of property value.

TABLE IV. - THEORETICAL ROCKET PERFORMANCE AT ASSIGNED TEMPERATURES FOR JP-4 FUEL WITH MIXTURES OF FLUORINE AND OZONE

[Combustion-chamber pressure, 600 lb/sq in. abs.]

(a) Equilibrium composition during isentropic expansion or compression.

Temperature, T, °K	Temperature exponent, n_T, $\left(\frac{\partial \ln T}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Static pressure, P, lb/sq in. abs	Enthalpy, h, cal/g	Molecular weight, M	Partial derivative, $\left(\frac{\partial M}{\partial T}\right)_s$, $(°K)^{-1}$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, c_p, $\frac{cal}{(g)(°K)}$	Absolute viscosity, micropoises	Thermal conductivity, cal/(cm)(sec)(°K)	Ratio of nozzle area to throat area	Coefficient of thrust, C_F	Specific-impulse exponent, n_I, $\left(\frac{\partial \ln I}{\partial \ln P_c}\right)_{\frac{P_c}{P}}$	Specific impulse, I, $\frac{lb\text{-}sec}{lb}$
β = 0 (pure ozone); r = 1.508 (30.70 percent fuel)													
4000	0.0482	934.810	4081.3	20.456	-.001617	1.1491	1.9006	975	0.00197				
3600	.0410	311.190	3682.4	21.142	-.001803	1.1394	1.8215	908	.00175	1.008	0.715	0.0143	141.9
3200	.0317	87.566	3284.5	21.877	-.001824	1.1343	1.5521	828	.00138	1.866	1.179	.0127	234.0
2800	.0175	22.536	2920.3	22.539	-.001384	1.1428	1.0751	754	.00089	4.908	1.482	.0108	294.0
2400	-.0025	6.373	2633.0	22.932	-.000592	1.1757	.6693	680	.00053	12.861	1.683	.0086	333.8
2000	-.0165	2.007	2413.4	23.063	-.000134	1.2108	.5091	602	.00037	31.273	1.821	.0064	361.3
1600	-.0204	.575	2220.4	23.085	-.000013	1.2232	.4726	516	.00030	82.046	1.935	.0046	383.9
1200	-.0202	.118	2030.7	23.086	-.000000	1.2171	.4825	425	.00025	284.88	2.040	.0031	404.8
β = 0.5 (37.25 percent fluorine); r = 1.508 (25.78 percent fuel)													
4400	0.0584	1146.800	3907.9	19.879	-.001365	1.1703	1.6496	1272	0.00226				
4000	.0465	475.900	3544.4	20.465	-.001563	1.1594	1.6632	1182	.00211	1.158	0.432	0.0160	89.2
3600	.0394	170.560	3172.2	21.187	-.001733	1.1499	1.5960	1088	.00187	1.251	.974	.0146	200.9
3200	.0297	52.770	2803.5	21.829	-.001726	1.1460	1.3602	993	.00146	2.596	1.305	.0131	269.1
2800	.0140	15.398	2471.8	22.442	-.001239	1.1600	.9275	897	.00093	6.402	1.543	.0118	318.3
2400	-.0079	5.065	2217.4	22.781	-.000488	1.2037	.5793	802	.00055	14.888	1.703	.0090	351.3
2000	-.0222	1.837	2023.3	22.887	-.000107	1.2449	.4506	703	.00039	31.929	1.616	.0068	374.6
β = 1.0 (54.29 percent fluorine); r = 1.506 (23.30 percent fuel)													
4400	0.0482	692.800	3556.9	20.166	-.001310	1.1718	1.4907	1410	0.00228				
4000	.0485	295.850	3209.8	20.719	-.001452	1.1643	1.4489	1313	.00206	1.015	0.745	0.0152	157.6
3600	.0356	112.390	2862.4	21.325	-.001564	1.1581	1.3548	1210	.00178	1.569	1.109	.0139	234.6
3200	.0258	38.199	2525.7	21.947	-.001496	1.1581	1.1367	1102	.00138	3.221	1.372	.0124	290.4
2800	.0090	12.717	2230.3	22.460	-.000988	1.1798	.7741	993	.00088	7.243	1.568	.0106	331.8
2400	-.0121	4.758	2005.2	22.722	-.000367	1.2292	.5118	883	.00055	15.113	1.701	.0086	360.1
2000	-.0245	1.888	1827.7	22.801	-.000080	1.2701	.4162	769	.00040	29.904	1.800	.0066	380.9
β = 1.942 (69.75 percent fluorine); r = 1.47 (20.48 percent fuel)													
4800	0.0490	874.470	3490.8	20.355	-.001888	1.1723	1.5131	1632	0.00267				
4400	.0427	399.730	3144.1	20.889	-.001376	1.1652	1.4335	1542	.00239	1.083	0.570	0.0159	183.4
4000	.0353	167.530	2801.4	21.448	-.001403	1.1609	1.2983	1445	.00204	1.257	.981	.0145	212.8
3600	.0261	65.324	2474.2	21.995	-.001307	1.1622	1.0846	1341	.00161	2.215	1.253	.0129	271.1
3200	.0134	24.845	2180.4	22.464	-.000989	1.1769	.8146	1228	.00114	4.365	1.454	.0111	314.8
2800	-.0077	10.257	1947.5	22.743	-.000370	1.2323	.5125	1105	.00069	8.303	1.596	.0092	345.5
2400	-.0236	4.931	1780.6	22.800	-.000023	1.2985	.3611	981	.00048	13.983	1.690	.0072	368.9
2000	.0036	1.922	1602.2	22.985	-.001144	1.2084	.6291	840	.00062	28.077	1.786	.0058	386.5
β = 1.942 (69.75 percent fluorine); r = 1.60 (20.81 percent fuel)													
4800	0.0488	863.700	3521.7	20.275	-.001279	1.1711	1.5283	1627	0.00269				
4400	.0426	393.760	3172.3	20.806	-.001370	1.1654	1.4356	1538	.00239	1.019	0.580	0.0158	126.0
4000	.0350	165.120	2828.5	21.359	-.001384	1.1611	1.2869	1442	.00202	1.266	.986	.0144	214.0
3600	.0255	64.789	2502.0	21.895	-.001266	1.1635	1.0660	1339	.00156	2.226	1.255	.0128	272.4
3200	.0126	25.001	2211.2	22.344	-.000942	1.1789	.7995	1228	.00112	4.339	1.453	.0110	315.4
2800	-.0044	10.249	1974.5	22.627	-.000466	1.2187	.5564	1108	.00074	8.325	1.596	.0091	346.6
2400	-.0207	4.612	1792.5	22.732	-.000092	1.2815	.4065	962	.00051	14.835	1.698	.0072	368.7
2000	-.0174	2.072	1639.1	22.756	-.000232	1.2825	.4150	848	.00044	26.225	1.780	.0055	386.4
β = 1.942 (69.75 percent fluorine); r = 1.506 (20.89 percent fuel)													
4800	0.0486	870.400	3529.5	20.262	-.001274	1.1705	1.5308	1626	0.00269				
4400	.0493	396.220	3179.3	20.790	-.001359	1.1643	1.4402	1537	.00240	1.020	0.576	0.0157	125.1
4000	.0348	166.050	2834.9	21.340	-.001374	1.1609	1.2841	1441	.00202	1.263	.984	.0143	213.6
3600	.0252	65.286	2508.8	21.871	-.001249	1.1639	1.0579	1338	.00157	2.215	1.253	.0127	272.0
3200	.0123	25.356	2219.5	22.312	-.000920	1.1802	.7902	1227	.00111	4.292	1.450	.0110	314.9
2800	-.0042	10.460	1984.3	22.589	-.000463	1.2194	.5555	1108	.00074	8.186	1.593	.0091	345.9
2400	-.0187	4.669	1800.1	22.700	-.000133	1.2725	.4214	982	.00052	14.689	1.696	.0072	368.3
2000	-.0248	2.077	1644.4	22.725	-.000019	1.3062	.3725	849	.00041	26.215	1.779	.0055	386.3
1600	-.0266	.825	1499.6	22.728	-.000001	1.3283	.3538	709	.00033	50.691	1.853	.0041	402.2

TABLE IV. - Concluded. THEORETICAL ROCKET PERFORMANCE AT ASSIGNED TEMPERATURES FOR

JP-4 FUEL WITH MIXTURES OF FLUORINE AND OZONE

[Combustion-chamber pressure, 600 lb/sq in. abs.]

(b) Frozen composition during isentropic expansion or compression.

Temperature, T, $^{\circ}K$	Static pressure, P, lb/sq in. abs	Enthalpy, h, cal/g	Specific heat, c_p, $\frac{cal}{(g)(^{\circ}K)}$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Absolute viscosity, micropoises	Thermal conductivity, cal/(cm)(sec)($^{\circ}K$)	Ratio of nozzle area to throat area	Coefficient of thrust, C_F	Specific impulse, I, $\frac{lb\text{-}sec}{lb}$
β = 0 (pure ozone); r = 1.508 (30.70 percent fuel)									
4000	751.780	3998.4	0.5013	1.236	971	0.00060			
3600	434.460	3798.9	.4962	1.239	907	.00056	1.08	0.519	100.0
3200	236.960	3601.6	.4902	1.243	841	.00051	1.06	.856	164.8
2800	120.280	3406.9	.4830	1.248	771	.00046	1.44	1.090	210.0
2400	55.714	3215.5	.4739	1.253	697	.00041	2.27	1.280	246.5
2000	22.871	3028.2	.4619	1.262	618	.00036	4.09	1.441	277.6
1600	7.951	2846.6	.4453	1.274	532	.00030	8.58	1.582	304.7
1200	2.164	2672.9	.4216	1.294	437	.00024	21.92	1.706	328.6
900	.632	2549.8	.3983	1.317	357	.00018	53.67	1.788	344.5
600	.124	2434.3	.3716	1.347	264	.00013	174.55	1.863	358.8
β = 0.5 (37.25 percent fluorine); r = 1.508 (25.78 percent fuel)									
4400	832.960	3772.2	0.4552	1.274	1265	0.00073			
4000	535.640	3590.9	.4512	1.277	1184	.00068	1.53	0.314	62.5
3600	330.280	3411.3	.4467	1.280	1099	.00063	1.00	.702	139.8
3200	193.490	3233.6	.4416	1.285	1011	.00057	1.13	.939	187.1
2800	106.340	3058.1	.4355	1.290	920	.00051	1.51	1.126	224.2
2400	53.861	2885.4	.4279	1.296	824	.00045	2.24	1.283	255.5
2000	24.488	2716.2	.4179	1.306	723	.00039	3.70	1.421	282.9
1600	9.585	2551.6	.4044	1.319	615	.00032	6.97	1.542	307.2
1200	2.998	2393.3	.3860	1.339	497	.00025	15.61	1.651	328.8
900	.988	2280.0	.3691	1.361	400	.00020	34.00	1.725	343.5
600	.223	2171.9	.3517	1.385	292	.00014	96.88	1.792	356.9
β = 1.0 (54.29 percent fluorine); r = 1.508 (23.30 percent fuel)									
4400	644.540	3525.8	0.4297	1.296	1410	0.00078			
4000	425.320	3354.7	.4259	1.299	1314	.00072	1.07	0.543	110.6
3600	269.760	3185.2	.4218	1.303	1216	.00066	1.02	.806	164.2
3200	163.010	3017.4	.4171	1.307	1115	.00060	1.21	1.001	203.9
2800	92.723	2851.6	.4116	1.313	1010	.00054	1.60	1.162	236.6
2400	48.819	2688.3	.4047	1.320	900	.00047	2.33	1.301	265.0
2000	23.198	2528.1	.3957	1.330	785	.00041	3.74	1.424	290.1
1600	9.558	2372.1	.3836	1.343	662	.00034	6.73	1.534	312.6
1200	3.176	2221.7	.3676	1.364	531	.00026	14.26	1.634	332.9
900	1.104	2113.6	.3535	1.384	425	.00020	29.55	1.702	346.7
600	.264	2009.6	.3401	1.405	307	.00014	79.48	1.765	359.5
β = 1.942 (69.75 percent fluorine); r = 1.47 (20.48 percent fuel)									
4800	716.400	3399.4	0.4065	1.311	1639	0.00086			
4400	497.220	3237.6	.4028	1.315	1535	.00080	1.28	0.406	84.2
4000	334.450	3077.1	.3994	1.318	1429	.00074	1.00	.700	145.1
3600	216.570	2918.1	.3957	1.322	1319	.00068	1.08	.901	186.8
3200	133.880	2760.6	.3916	1.327	1206	.00062	1.32	1.063	220.4
2800	78.093	2605.0	.3866	1.332	1089	.00055	1.75	1.202	249.3
2400	42.288	2451.5	.3805	1.339	968	.00048	2.51	1.325	274.8
2000	20.748	2300.9	.3724	1.349	840	.00041	3.93	1.436	297.7
1600	8.871	2154.0	.3616	1.363	707	.00034	6.88	1.536	318.4
1200	3.080	2012.1	.3475	1.384	564	.00026	14.02	1.627	337.2
900	1.112	1909.6	.3356	1.403	448	.00020	28.05	1.689	350.2
600	.278	1810.6	.3252	1.421	322	.00014	72.36	1.748	362.3
β = 1.942 (69.75 percent fluorine); r = 1.50 (20.81 percent fuel)									
4800	711.830	3432.6	0.4087	1.310	1634	0.00087			
4400	493.870	3269.9	.4050	1.314	1531	.00081	1.26	0.413	85.9
4000	332.070	3108.6	.4016	1.318	1424	.00074	1.00	.704	146.4
3600	214.940	2948.7	.3979	1.322	1315	.00068	1.08	.904	188.0
3200	132.800	2790.3	.3937	1.326	1203	.00062	1.32	1.066	221.6
2800	77.423	2633.8	.3887	1.332	1086	.00055	1.75	1.204	250.5
2400	41.900	2479.5	.3825	1.339	965	.00049	2.52	1.327	276.0
2000	20.544	2328.1	.3744	1.349	838	.00042	3.96	1.437	298.9
1600	8.777	2180.4	.3635	1.363	705	.00034	6.93	1.537	319.7
1200	3.044	2037.7	.3493	1.384	562	.00026	14.15	1.628	338.5
900	1.099	1934.7	.3373	1.403	447	.00020	28.33	1.690	351.5
600	.274	1835.2	.3268	1.421	322	.00014	73.15	1.749	363.6
β = 1.942 (69.75 percent fluorine); r = 1.508 (20.89 percent fuel)									
4800	714.270	3438.4	0.4093	1.310	1633	0.00087			
4400	495.420	3275.5	.4055	1.314	1530	.00081	1.27	0.410	85.3
4000	332.980	3114.0	.4021	1.317	1424	.00074	1.00	.702	146.0
3600	215.460	2953.9	.3984	1.321	1314	.00068	1.08	.903	187.8
3200	133.070	2795.3	.3942	1.326	1202	.00062	1.32	1.065	221.5
2800	77.545	2638.6	.3892	1.331	1085	.00055	1.75	1.204	250.4
2400	41.945	2484.1	.3830	1.339	964	.00049	2.52	1.327	275.9
2000	20.554	2332.5	.3748	1.348	838	.00042	3.96	1.437	298.9
1600	8.776	2184.6	.3639	1.363	704	.00034	6.94	1.537	319.7
1200	3.042	2041.8	.3497	1.383	562	.00026	14.17	1.628	338.5
900	1.097	1938.7	.3376	1.402	447	.00020	28.38	1.691	351.5
600	.274	1839.1	.3271	1.421	321	.00014	73.33	1.749	363.7

TABLE V. - EQUILIBRIUM COMPOSITION OF PRODUCTS OF REACTION AT COMBUSTION TEMPERATURE AND AT ASSIGNED TEMPERATURES FOR ISENTROPIC EXPANSION OR COMPRESSION[a]

[Combustion-chamber pressure, 600 lb/sq in. abs.]

β = 0 (pure ozone); r = 1.508 (30.70 percent fuel)

T, $^{\circ}$K	[b]3831	1200	1600	2000	2400	2800	3200	3600	4000
CO	0.37377	0.27978	0.32666	0.34934	0.36013	0.36531	0.36974	0.37292	0.37396
CO_2	.08192	.22757	.18065	.15748	.14383	.13000	.11103	.09169	.07557
H	.06647	0	.00012	.00174	.00906	.02391	.04120	.05759	.07269
H_2	.13228	.22756	.18059	.15677	.14161	.13183	.12910	.13070	.13345
H_2O	.24462	.26509	.31197	.33434	.34145	.32954	.29999	.26457	.23081
O	.02121	0	0	0	.00019	.00810	.00773	.01597	.02508
O_2	.01501	0	0	0	.00018	.00202	.00689	.01237	.01661
OH	.06473	0	.00001	.00032	.00355	.01529	.03432	.05419	.07183

β = 0.5 (37.25 percent fluorine); r = 1.508 (25.78 percent fuel)

T, $^{\circ}$K	[b]4100	2000	2400	2800	3200	3600	4000	4400
CO	0.33733	0.32297	0.32919	0.33194	0.33523	0.33759	0.33764	0.33580
CO_2	.03759	.09947	.09131	.08229	.06769	.05236	.04010	.03114
F	.00966	0	.00007	.00051	.00186	.00444	.00844	.01388
H	.08292	.00144	.00805	.02271	.04138	.06035	.07856	.09560
H_2	.07950	.09885	.08879	.08126	.07847	.07665	.07936	.07979
HF	.28593	.33306	.33146	.32608	.31581	.30300	.28937	.27542
H_2O	.07634	.14403	.14868	.14152	.12260	.10043	.08067	.06478
O	.03154	0	.00017	.00214	.00863	.01838	.02896	.03898
O_2	.01160	0	.00011	.00144	.00517	.00898	.01127	.01215
OH	.04759	.00018	.00219	.01012	.02318	.03582	.04563	.05246

β = 1.0 (54.29 percent fluorine); r = 1.508 (23.30 percent fuel)

T, $^{\circ}$K	[b]4329	2000	2400	2800	3800	3600	4000	4400
CO	0.32148	0.31806	0.32126	0.32217	0.32401	0.32522	0.32408	0.32081
CO_2	.01643	.06222	.05770	.05242	.04203	.03044	.02154	.01553
F	.03252	.00001	.00013	.00108	.00431	.01094	.02139	.03517
H	.08918	.00112	.00655	.01946	.03717	.05503	.07460	.09223
H_2	.04476	.06171	.05528	.04928	.04583	.04468	.04448	.04487
HF	.41150	.49969	.49783	.49113	.47668	.45640	.43268	.40678
H_2O	.01996	.05711	.05994	.05632	.04600	.03443	.02531	.01902
O	.03248	0	.00011	.00170	.00766	.01683	.02607	.03368
O_2	.00555	0	.00005	.00075	.00294	.00796	.00568	.00548
OH	.02614	.00009	.00115	.00569	.01337	.02007	.02425	.02642

β = 1.942 (69.75 percent fluorine; r = 1.47 (20.48 percent fuel)

T, $^{\circ}$K	[b]4602	2000	2400	2800	3200	3600	4000	4400	4800
C(GAS)	0.00002	0	0	0	0	0	0	0.00001	0.00003
CF	.00002	0	0	0	0	0	0	.00001	.00003
CF_4	0	.00201	0	0	0	0	0	0	0
CO	.30124	.32440	.32579	.32544	.32356	.31915	.31855	.30506	.29755
CO_2	.00095	.01057	.00847	.00797	.00577	.00331	.00188	.00117	.00080
F	.12102	.00860	.01657	.01911	.03188	.05373	.08004	.10745	.13394
F_2	.00001	0	0	0	0	0	0	0	.00001
H	.07464	0	.00007	.00179	.01011	.02531	.04443	.06463	.08417
H_2	.01459	0	.00001	.00034	.00221	.00530	.00894	.01271	.01639
HF	.48081	.65443	.64908	.64487	.62397	.58843	.54613	.50839	.46028
H_2O	.00041	0	0	.00006	.00030	.00045	.00046	.00043	.00039
O	.00474	0	.00002	.00032	.00162	.00321	.00417	.00462	.00482
O_2	.00005	0	0	.00002	.00009	.00011	.00008	.00006	.00004
OH	.00151	0	0	.00008	.00050	.00101	.00131	.00146	.00155

β = 1.942 (69.75 percent fluorine); r = 1.50 (20.81 percent fuel)

T, $^{\circ}$K	b4609	2000	2400	2800	3200	3600	4000	4400	4800
C(GAS)	0.00008	0	0	0	0	0	0	0.00003	0.00015
CF	.00007	0	0	0	0	0	.00001	.00003	.00013
CF_4	0	.00015	0	0	0	0	0	0	0
CO	.30539	.33704	.33700	.33556	.33176	.32553	.31781	.30964	.30156
CO_2	.00020	.00181	.00165	.00152	.00110	.00064	.00037	.00024	.00018
F	.11591	.00263	.00378	.00961	.02428	.04691	.07384	.10171	.12844
F_2	.00001	0	0	0	0	0	0	0	.00001
H	.07982	0	.00031	.00359	.01322	.02929	.04895	.06941	.08898
H_2	.01637	0	.00018	.00135	.00379	.00704	.01069	.01444	.01809
HF	.48070	.65837	.65713	.64824	.62532	.58954	.54713	.50314	.46086
H_2O	.00010	0	0	.00004	.00010	.00011	.00011	.00010	.00010
O	.00101	0	0	.00006	.00030	.00061	.00081	.00093	.00111
OH	.00034	0	0	.00003	.00012	.00022	.00028	.00031	.00037

β = 1.942 (69.75 percent fluorine); r = 1.508 (20.89 percent fuel)

T, $^{\circ}$K	b4606	1600	2000	2400	2800	3200	3600	4000	4400	4800
C(GAS)	0.00025	0	0	0	0	0	0.00001	0.00005	0.00016	0.00037
CF	.00023	0	0	0	0	.00001	.00002	.00006	.00015	.00032
CF_2	.00001	0	0	0	0	0	0	0	.00001	.00001
CF_4	0	.00001	0	0	0	0	0	0	0	0
C_2F_2	.00001	0	0	0	0	0	0	0	.00001	.00001
CO	.30623	.33988	.33985	.33948	.33781	.33365	.32702	.31899	.31054	.30222
CO_2	.00006	.00001	0	0	0	.00001	.00002	.00003	.00005	.00008
F	.11388	0	.00019	.00175	.00801	.02261	.04521	.07214	.09997	.12660
F_2	.00001	0	0	0	0	0	0	0	0	.00001
H	.08043	0	.00004	.00066	.00421	.01400	.03017	.04987	.07026	.08970
H_2	.01678	.00002	.00008	.00055	.00190	.00431	.00753	.01116	.01489	.01853
HF	.48167	.66008	.65983	.65755	.64805	.62540	.58998	.54759	.50368	.46151
H_2O	.00003	0	0	0	0	0	0	.00001	.00002	.00004
O	.00031	0	0	0	0	0	.00002	.00007	.00019	.00045
OH	.00010	0	0	0	0	0	.00001	.00002	.00007	.00016

[a]Compositions given as mole fractions; those less than 5×10^{-6} are shown as 0.

[b]Combustion-chamber conditions.

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TABLE VI. - THEORETICAL ROCKET PERFORMANCE AT VARIOUS PRESSURE RATIOS FOR MIXTURES OF LIQUID OZONE AND FLUORINE WITH JP-4 FUEL

[Combustion-chamber pressure, 600 lb/sq in. abs.]

(a) Equilibrium composition during isentropic expansion.

Pressure ratio, P_c/P	Static pressure, P, lb/sq in. abs	Temperature, T, °K	Temperature exponent, n_T, $\left(\frac{\partial \ln T}{\partial \ln P_c}\right)_{P_c/P}$	Enthalpy, h, cal/g	Molecular weight, M	Partial derivative, $\left(\frac{\partial M}{\partial T}\right)_s$, $(°K)^{-1}$	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, c_p, $\frac{cal}{(g)(°K)}$	Ratio of nozzle area to throat area	Coefficient of thrust, C_F	Specific-impulse exponent, n_I, $\left(\frac{\partial \ln I}{\partial \ln P_c}\right)_{P_c/P}$	Specific impulse, I, $\frac{lb\text{-}sec}{lb}$
β = 0 (pure ozone); r = 1.508 (30.70 percent fuel)												
1	600	3831	0.0455	3913.8	20.74	-.00170	1.145	1.887				
1.040	576.92	3817	.0452	3899.4	20.76	-.00171	1.145	1.884	2.357	0.178	0.0151	35.4
1.446	415.07	3699	.0430	3781.6	20.97	-.00176	1.142	1.857	1.036	.541	.0147	107.3
[a]1.735	345.89	3636	.0417	3718.4	21.08	-.00179	1.140	1.835	1.000	.657	.0144	130.4
2.168	276.71	3561	.0401	3642.9	21.21	-.00182	1.139	1.804	1.033	.774	.0142	153.5
10	60	3088	0.0283	3177.1	22.08	-.00175	1.135	1.429	2.41	1.276	0.0122	253.2
20	30	2885	.0210	2992.2	22.42	-.00151	1.139	1.180	3.96	1.427	.0112	283.2
20.41	29.392	2879	.0208	2986.9	22.42	-.00151	1.139	1.172	4.02	1.431	.0112	284.0
40	15	2676	.0132	2822.3	22.69	-.00113	1.152	.930	6.67	1.553	.0101	308.2
40.83	14.696	2670	.0129	2817.5	22.70	-.00112	1.152	.923	6.78	1.557	.0101	308.9
60	10	2549	.0070	2729.8	22.82	-.00087	1.162	.796	9.10	1.618	.0094	321.0
100	6	2380	-.0034	2620.5	22.94	-.00056	1.178	.657	13.47	1.691	.0085	335.5
300	2	1999	-.0165	2412.8	23.06	-.00013	1.210	.509	31.35	1.822	.0064	361.4
β = 0.5 (37.25 percent fluorine); r = 1.508 (25.78 percent fuel)												
1	600	4100	0.0481	3635.8	20.31	-.00151	1.162	1.665				
1.040	576.92	4082	.0478	3620.1	20.34	-.00152	1.162	1.665	2.368	0.179	0.0163	36.9
1.454	412.78	3941	.0455	3489.6	20.56	-.00159	1.158	1.660	1.035	.547	.0158	112.8
[a]1.744	343.97	3867	.0442	3421.0	20.68	-.00163	1.156	1.653	1.000	.663	.0156	136.7
2.180	275.18	3779	.0427	3339.4	20.82	-.00167	1.154	1.641	1.033	.779	.0153	160.6
10	60	3242	0.0308	2841.2	21.76	-.00174	1.146	1.394	2.38	1.275	0.0132	263.0
20	30	3018	.0234	2644.8	22.13	-.00156	1.149	1.171	3.89	1.424	.0123	293.7
20.41	29.392	3011	.0232	2639.2	22.14	-.00155	1.149	1.163	3.95	1.428	.0122	294.5
40	15	2791	.0137	2465.3	22.45	-.00122	1.161	.918	6.53	1.547	.0111	319.1
40.83	14.696	2784	.0135	2460.2	22.46	-.00121	1.162	.911	6.63	1.550	.0111	319.8
60	10	2652	.0083	2367.9	22.60	-.00095	1.175	.777	8.88	1.610	.0104	332.2
100	6	2465	-.0030	2253.4	22.75	-.00059	1.196	.622	13.09	1.681	.0093	346.8
300	2	2033	-.0241	2038.2	22.88	-.00011	1.242	.451	29.96	1.808	.0070	372.9
β = 1.0 (54.29 percent fluorine); r = 1.508 (23.30 percent fuel)												
1	600	4329	0.0473	3495.2	20.26	-.00133	1.171	1.485				
1.040	576.92	4309	.0471	3478.6	20.29	-.00134	1.170	1.483	2.374	0.180	0.0161	38.0
1.458	411.40	4149	.0448	3339.3	20.51	-.00140	1.167	1.468	1.035	.550	.0156	116.5
[a]1.750	342.83	4066	.0435	3266.9	20.62	-.00143	1.166	1.458	1.000	.666	.0154	140.9
2.188	274.26	3967	.0420	3180.9	20.77	-.00146	1.164	1.444	1.032	.781	.0151	165.4
10	60	3364	0.0300	2660.6	21.70	-.00156	1.156	1.244	2.35	1.273	0.0131	269.5
20	30	3114	.0229	2456.8	22.07	-.00141	1.160	1.062	3.83	1.420	.0121	300.6
20.41	29.392	3106	.0226	2451.1	22.08	-.00141	1.161	1.055	3.89	1.424	.0120	301.4
40	15	2862	.0122	2271.7	22.40	-.00108	1.175	.829	6.40	1.542	.0109	326.3
40.83	14.696	2854	.0118	2266.5	22.40	-.00107	1.175	.822	6.50	1.545	.0109	327.0
60	10	2707	.0055	2171.8	22.54	-.00083	1.191	.700	8.67	1.603	.0102	339.3
100	6	2499	-.0055	2054.9	22.68	-.00050	1.217	.562	12.71	1.673	.0091	354.0
300	2	2025	-.0257	1837.9	22.80	-.00008	1.268	.416	28.66	1.794	.0067	379.7
β = 1.942 (69.75 percent fluorine); r = 1.47 (20.48 percent fuel)												
1	600	4602	0.0460	3319.1	20.62	-.00134	1.169	1.481				
1.040	576.92	4582	.0457	3301.7	20.64	-.00134	1.168	1.477	2.373	0.180	0.0165	38.9
1.458	411.56	4414	.0429	3156.3	20.87	-.00137	1.165	1.437	1.035	.550	.0159	119.0
[a]1.749	342.98	4327	.0414	3080.7	20.99	-.00139	1.164	1.412	1.000	.665	.0156	144.0
2.187	274.37	4222	.0395	2990.7	21.14	-.00140	1.163	1.379	1.032	.781	.0153	169.0
10	60	3565	0.0250	2446.7	22.04	-.00129	1.162	1.063	2.34	1.273	0.0127	275.5
20	30	3279	.0158	2234.5	22.38	-.00108	1.171	.872	3.81	1.419	.0115	307.2
20.41	29.392	3270	.0155	2228.6	22.39	-.00107	1.172	.866	3.87	1.423	.0115	308.0
40	15	2981	.0021	2043.0	22.65	-.00066	1.201	.634	6.31	1.540	.0101	333.2
40.83	14.696	2971	.0017	2037.6	22.66	-.00065	1.202	.629	6.41	1.543	.0101	333.9
60	10	2786	-.0083	1940.6	22.75	-.00035	1.235	.505	8.47	1.600	.0091	346.3
100	6	2509	-.0213	1822.5	22.80	-.00005	1.287	.396	12.18	1.667	.0077	360.9
300	2	2013	.0040	1609.2	22.97	-.00104	1.216	.605	27.22	1.782	.0058	385.7
β = 1.942 (69.75 percent fluorine); r = 1.50 (20.81 percent fuel)												
1	600	4609	0.0460	3354.8	20.52	-.00133	1.168	1.490				
1.040	576.92	4589	.0457	3337.3	20.55	-.00133	1.168	1.485	2.373	0.179	0.0164	39.0
1.458	411.55	4421	.0429	3191.0	20.78	-.00137	1.166	1.442	1.035	.550	.0159	119.4
[a]1.749	342.96	4334	.0414	3114.9	20.90	-.00138	1.164	1.415	1.000	.665	.0156	144.5
2.187	274.37	4229	.0395	3024.3	21.04	-.00139	1.163	1.380	1.032	.781	.0152	169.6
10	60	3568	0.0245	2477.1	21.94	-.00125	1.164	1.045	2.34	1.273	0.0127	276.4
20	30	3278	.0153	2263.7	22.27	-.00102	1.174	.851	3.80	1.419	.0114	308.1
20.41	29.392	3269	.0150	2257.8	22.28	-.00101	1.175	.846	3.86	1.423	.0114	309.0
40	15	2976	.0039	2071.4	22.53	-.00068	1.198	.655	6.30	1.539	.0100	334.2
40.83	14.696	2967	.0035	2066.0	22.53	-.00066	1.199	.649	6.39	1.542	.0099	334.9
60	10	2788	-.0047	1968.5	22.63	-.00045	1.221	.550	8.48	1.600	.0091	347.3
100	6	2536	-.0142	1849.3	22.71	-.00018	1.263	.443	12.28	1.667	.0079	361.9
300	2	1985	-.0164	1632.9	22.76	-.00026	1.280	.421	26.92	1.783	.0055	387.1
β = 1.942 (69.75 percent fluorine); r = 1.508 (20.89 percent fuel)												
1	600	4606	0.0457	3359.0	20.51	-.00132	1.167	1.494				
1.040	576.92	4586	.0454	3341.6	20.54	-.00133	1.167	1.490	2.373	0.179	0.0163	39.0
1.458	411.66	4418	.0427	3195.4	20.77	-.00136	1.165	1.446	1.035	.550	.0158	119.3
[a]1.749	343.05	4331	.0411	3119.3	20.88	-.00137	1.163	1.418	1.000	.665	.0155	144.4
2.186	274.43	4185	.0395	3028.8	21.03	-.00138	1.162	1.381	1.022	.781	.0150	169.5
10	60	3565	0.0242	2481.3	21.92	-.00123	1.165	1.035	2.34	1.273	0.0126	276.4
20	30	3272	.0149	2268.1	22.24	-.00099	1.176	.838	3.80	1.419	.0113	308.1
20.41	29.392	3263	.0146	2262.1	22.25	-.00098	1.176	.832	3.86	1.423	.0112	308.9
40	15	2968	.0036	2075.9	22.50	-.00065	1.201	.644	6.29	1.539	.0099	334.1
40.83	14.696	2958	.0032	2070.6	22.50	-.00064	1.202	.639	6.38	1.542	.0098	334.8
60	10	2778	-.0050	1973.2	22.60	-.00044	1.222	.546	8.46	1.599	.0090	347.3
100	6	2527	-.0140	1854.3	22.68	-.00022	1.256	.454	12.26	1.667	.0078	361.9
300	2	1982	-.0251	1637.9	22.73	-.00002	1.309	.371	26.93	1.782	.0054	387.0

[a]Throat.

TABLE VI. - Concluded. THEORETICAL ROCKET PERFORMANCE AT VARIOUS PRESSURE RATIOS FOR MIXTURES OF LIQUID OZONE AND FLUORINE WITH JP-4 FUEL

[Combustion-chamber pressure, 600 lb/sq in. abs.]

(b) Frozen composition during isentropic expansion.

Pressure ratio, P_o/P	Static pressure, P, lb/sq in. abs	Temperature, T, °K	Enthalpy, h, cal/g	Isentropic exponent, γ, $\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	Specific heat, $\frac{cal}{(g)(^{\circ}K)}$	Ratio of nozzle area to throat area	Coefficient of thrust, C_F	Specific impulse, I, $\frac{lb\text{-}sec}{lb}$
β = 0:(pure ozone); r = 1.508 (30.70 percent fuel)								
1	600	3831	3913.8	1.238	0.499			
1.040	576.92	3802	3899.5	1.238	.499	2.422	0.183	35.3
1.497	400.73	3544	3771.2	1.240	.495	1.031	.578	111.4
1.797	333.94	3421	3710.4	1.241	.494	1.000	.691	133.0
2.246	267.16	3276	3638.8	1.242	.491	1.029	.803	154.7
10	60	2436	3232.6	1.253	0.475	2.17	1.264	243.5
20	30	2115	3081.7	1.259	.466	3.40	1.397	269.1
20.41	29.392	2106	3077.6	1.259	.465	3.45	1.400	269.8
40	15	1831	2950.8	1.266	.456	5.48	1.503	289.5
40.83	14.696	1823	2947.2	1.267	.455	5.56	1.506	290.0
60	10	1681	2882.6	1.271	.449	7.29	1.555	299.5
100	6	1505	2804.7	1.278	.440	10.49	1.613	310.7
300	2	1179	2664.0	1.296	.420	23.21	1.712	329.8
β = 0.5 (37.25 percent fluorine); r = 1.508 (23.78 percent fuel)								
1	600	4100	3635.8	1.276	0.452			
1.040	576.92	4065	3620.2	1.276	.452	2.448	0.185	36.9
1.517	395.43	3744	3475.9	1.279	.448	1.030	.592	118.0
1.821	329.53	3598	3410.5	1.280	.447	1.000	.703	140.0
2.276	263.62	3426	3333.8	1.282	.445	1.028	.814	162.1
10	60	2460	2911.1	1.295	0.429	2.09	1.261	251.1
20	30	2097	2756.8	1.303	.421	3.24	1.389	276.6
20.41	29.392	2087	2752.7	1.303	.420	3.28	1.392	277.2
40	15	1782	2625.6	1.312	.411	5.14	1.489	296.5
40.83	14.696	1773	2622.0	1.313	.411	5.21	1.492	297.0
60	10	1616	2558.2	1.318	.405	6.77	1.538	306.2
100	6	1427	2482.3	1.327	.397	9.63	1.591	316.8
300	2	1082	2348.2	1.347	.380	20.73	1.681	334.7
β = 1.0 (54.29 percent fluorine); r = 1.508 (23.30 percent fuel)								
1	600	4329	3495.2	1.296	0.429			
1.040	576.92	4290	3478.6	1.297	.429	2.461	0.186	38.0
1.528	392.68	3927	3323.7	1.300	.425	1.029	.600	122.2
1.834	327.24	3765	3254.9	1.301	.424	1.000	.710	144.6
2.292	261.78	3575	3174.6	1.303	.422	1.028	.820	167.0
10	60	2583	2738.1	1.318	0.407	2.06	1.260	256.7
20	30	2131	2580.2	1.326	.399	3.16	1.385	282.8
20.41	29.392	2120	2575.9	1.326	.399	3.21	1.388	282.8
40	15	1794	2447.1	1.336	.390	4.98	1.482	302.0
40.83	14.696	1785	2443.5	1.336	.390	5.04	1.485	302.5
60	10	1619	2379.3	1.343	.384	6.53	1.530	311.6
100	6	1419	2303.3	1.352	.377	9.23	1.581	322.0
300	2	1060	2170.5	1.373	.361	19.61	1.666	339.5
β = 1.942 (69.75 percent fluorine); r = 1.47 (20.48 percent fuel)								
1	600	4602	3319.1	1.313	0.405			
1.040	576.92	4559	3301.8	1.313	.404	2.471	0.187	38.8
1.537	390.47	4152	3138.0	1.317	.401	1.028	.606	125.5
1.844	325.40	3974	3066.6	1.318	.399	1.000	.715	148.2
2.305	260.31	3765	2983.4	1.320	.397	1.027	.824	170.9
10	60	2621	2536.1	1.335	0.384	2.03	1.259	261.0
20	30	2199	2375.4	1.344	.377	3.11	1.382	286.5
20.41	29.392	2188	2371.1	1.344	.376	3.15	1.385	287.2
40	15	1838	2240.9	1.354	.368	4.86	1.478	306.3
40.83	14.696	1828	2237.3	1.355	.368	4.92	1.480	306.8
60	10	1652	2172.7	1.361	.363	6.35	1.524	315.8
100	6	1441	2096.7	1.371	.356	8.94	1.573	326.1
300	2	1064	1965.0	1.392	.348	18.80	1.656	343.3
β = 1.942 (69.75 percent fluorine); r = 1.50 (20.81 percent fuel)								
1	600	4609	3354.8	1.312	0.407			
1.040	576.92	4566	3337.3	1.313	.406	2.471	0.187	38.9
1.536	390.53	4159	3172.6	1.316	.403	1.028	.605	125.9
1.844	325.44	3981	3100.8	1.318	.401	1.000	.715	148.7
2.305	260.35	3772	3017.1	1.320	.399	1.027	.824	171.4
10	60	2627	2566.8	1.335	0.386	2.03	1.259	261.8
20	30	2204	2405.1	1.343	.379	3.11	1.382	287.5
20.41	29.392	2193	2400.7	1.344	.379	3.15	1.386	288.1
40	15	1843	2269.6	1.354	.370	4.86	1.478	307.3
40.83	14.696	1833	2265.9	1.354	.370	4.93	1.480	307.8
60	10	1656	2200.9	1.361	.365	6.35	1.524	316.9
100	6	1445	2124.3	1.370	.358	8.94	1.573	327.2
300	2	1067	1991.6	1.392	.344	18.83	1.656	344.4
β = 1.942 (69.75 percent fluorine); r = 1.508 (20.89 percent fuel)								
1	600	4606	3359.0	1.312	0.407			
1.040	576.92	4563	3341.6	1.312	.407	2.471	0.187	38.9
1.536	390.58	4156	3177.0	1.316	.403	1.028	.605	125.9
1.843	325.49	3978	3105.2	1.318	.402	1.000	.715	148.6
2.304	260.38	3769	3021.5	1.320	.400	1.027	.824	171.4
10	60	2626	2571.2	1.334	0.387	2.03	1.259	261.8
20	30	2204	2409.4	1.343	.379	3.11	1.382	287.5
20.41	29.392	2193	2405.1	1.343	.379	3.15	1.386	288.1
40	15	1843	2273.9	1.353	.371	4.86	1.478	307.3
40.83	14.696	1833	2270.2	1.354	.371	4.93	1.480	307.8
60	10	1656	2205.8	1.360	.366	6.36	1.524	316.9
100	6	1445	2128.6	1.370	.359	8.95	1.574	327.2
300	2	1067	1995.8	1.391	.344	18.84	1.656	344.4

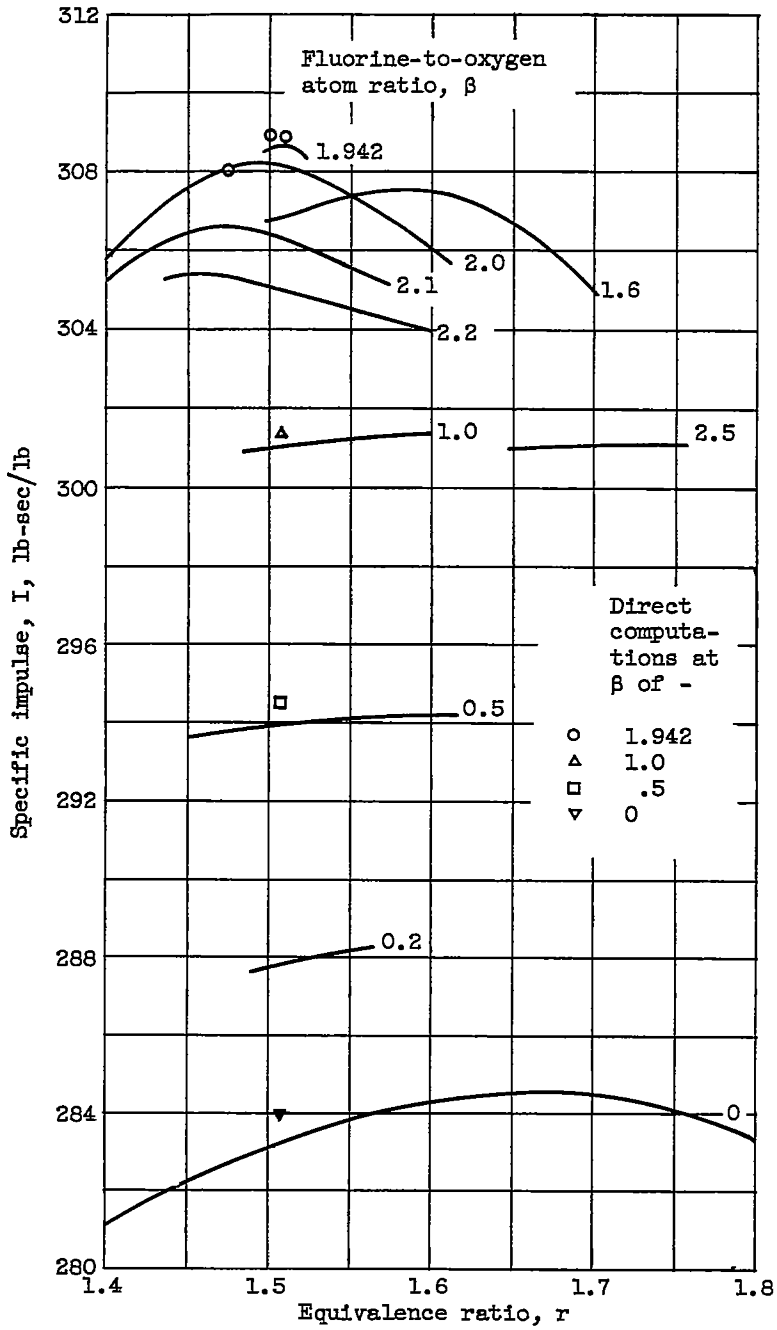

Figure 1. - Theoretical equilibrium specific impulse of JP-4 fuel with liquid-ozone - liquid-fluorine mixtures. Data calculated by means of equation (2). Combustion-chamber pressure, 600 pounds per square inch absolute; isentropic expansion to 2 atmospheres; pressure ratio, 20.41.

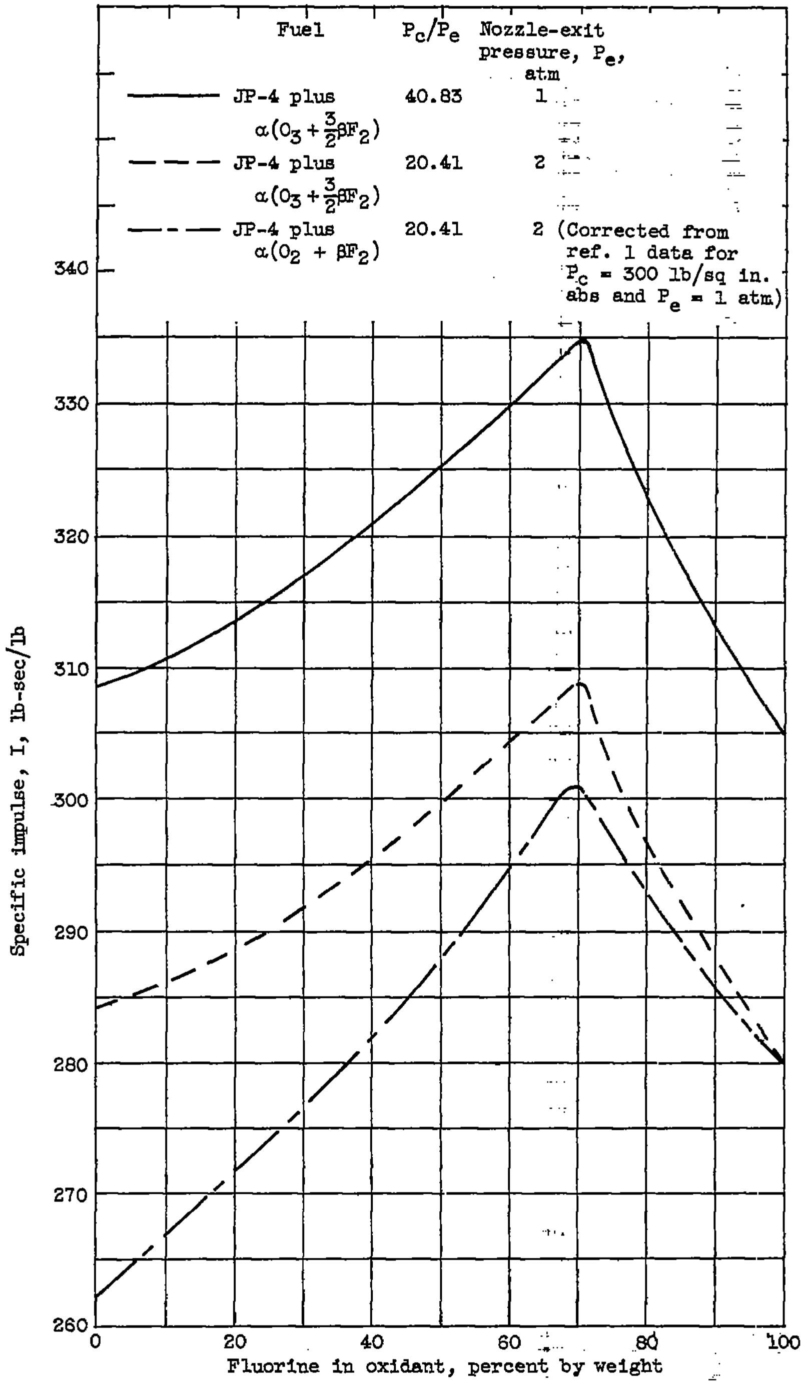

Figure 2. - Theoretical specific impulse of JP-4 fuel with liquid-ozone - liquid-fluorine mixtures and with liquid-oxygen - liquid-fluorine mixtures at equivalence ratios for which equilibrium specific impulse is maximum. Isentropic expansion from 600 pounds per square inch absolute to pressure ratio indicated assuming equilibrium composition.

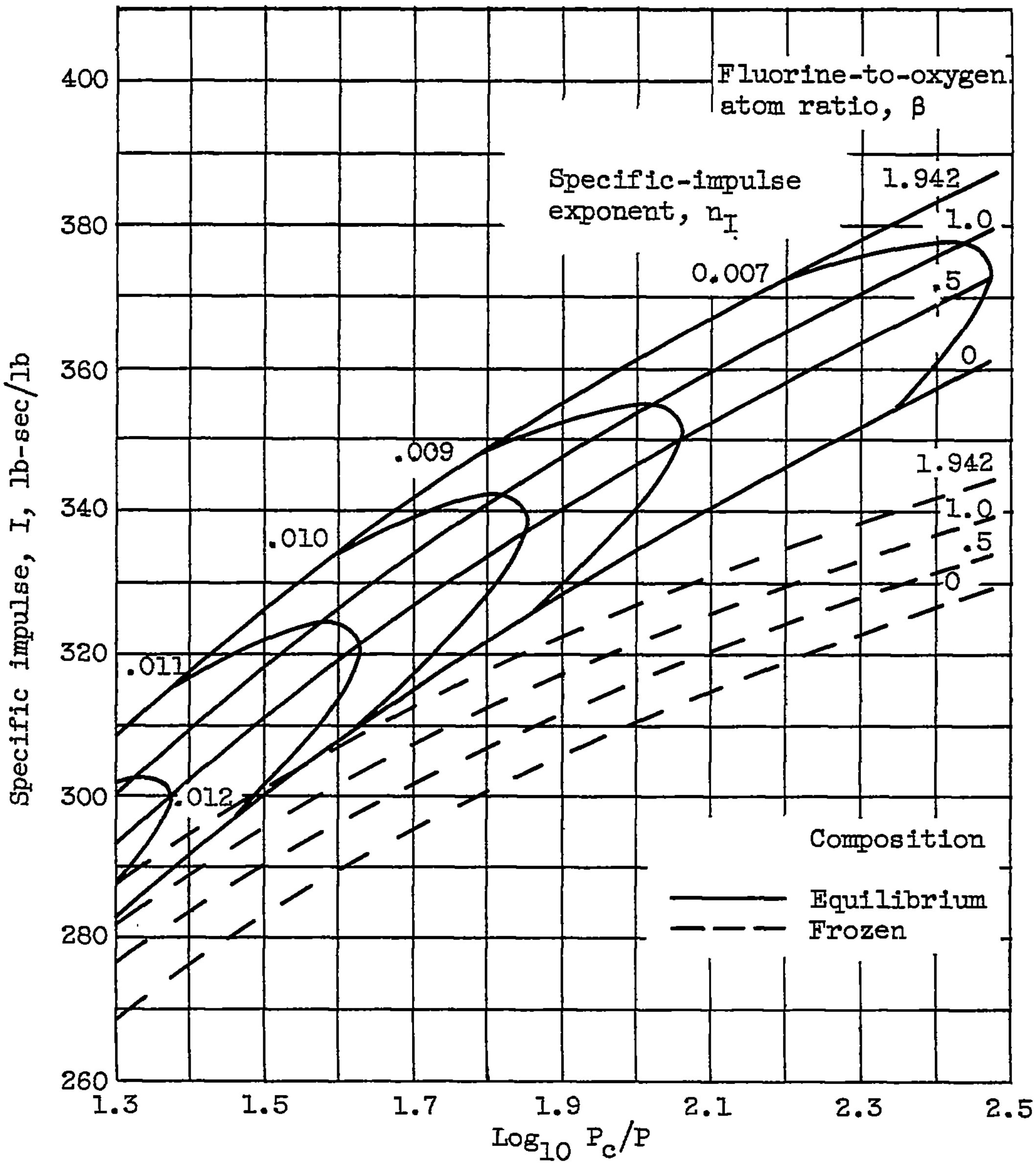

Figure 3. - Theoretical specific impulse plotted against logarithm of nozzle pressure ratio for JP-4 fuel with liquid-ozone - liquid-fluorine mixtures at equivalence ratio of 1.508. Isentropic expansion from combustion-chamber pressure of 600 pounds per square inch absolute.

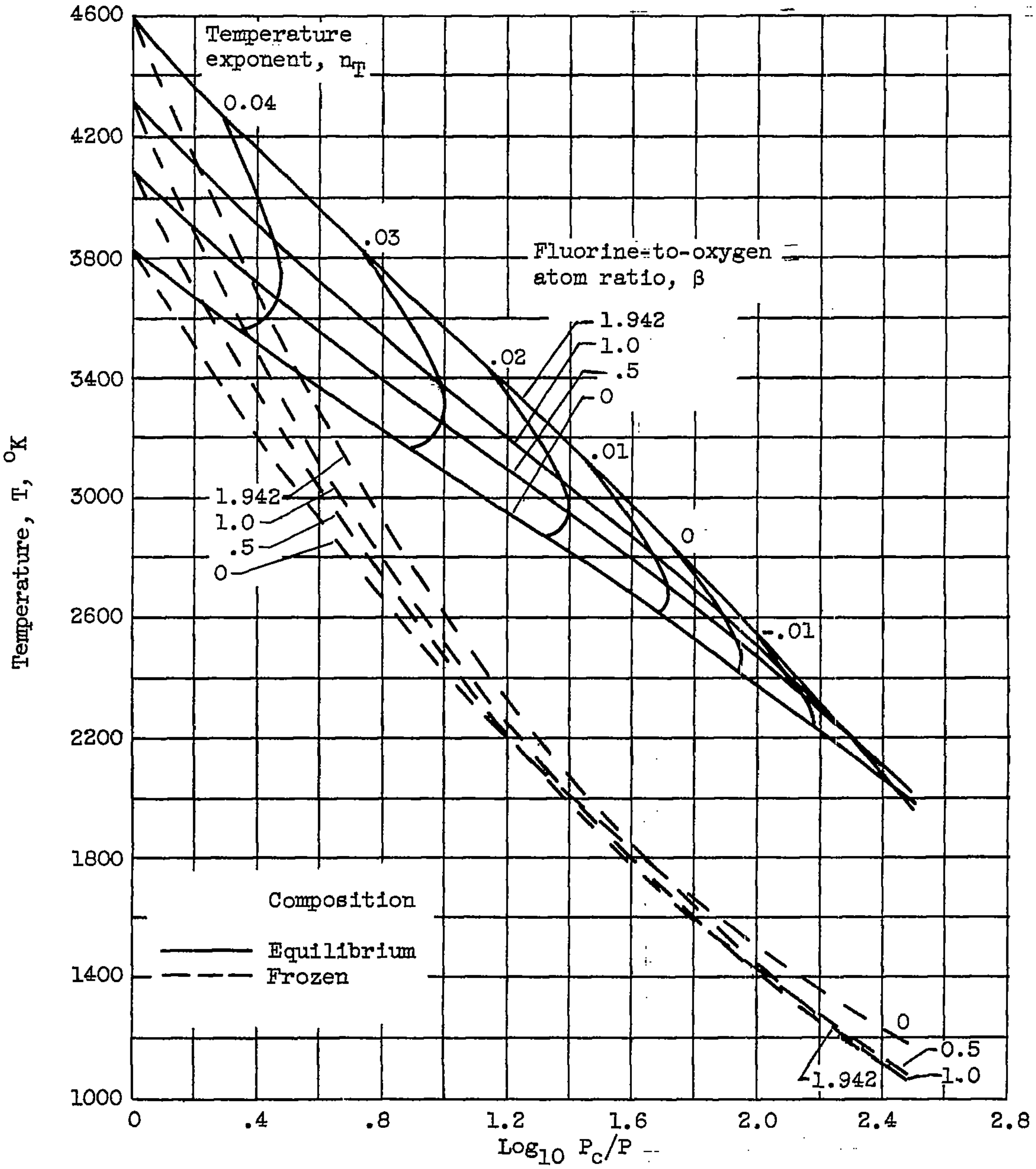

Figure 4. - Theoretical nozzle-exit temperature plotted against logarithm of nozzle pressure ratio for JP-4 fuel with liquid-ozone - liquid-fluorine mixtures at equivalence ratio of 1.508. Isentropic expansion from combustion-chamber pressure of 600 pounds per square inch absolute.